Strategies for Managing Massive Defects of the Foot in High-Energy Combat Injuries of the Lower Extremity

John J. Keeling, MD[a,b,c,d,e,*], Joseph R. Hsu, MD[f,g], Scott B. Shawen, MD[c,d,h,i], Romney C. Andersen, MD[c,d,e]

KEYWORDS

- Open fracture • Calcaneus fracture • Midfoot fracture
- Segmental bone loss • Bone graft

Blast-related lower extremity trauma presents many challenges in its management that are not frequently experienced in high-energy civilian trauma. The large amount of kinetic energy imparted from irregularly shaped projectiles creates a wide zone of soft tissue and bone injury.[1–4] Moreover, the "outside-in" mechanism of the blast frequently results in a considerable amount of wound contamination from clothing, footwear, and environmental contaminants. Also, the bony component of these

[a] Orthopaedic Surgery Service, National Naval Medical Center, 8901 Rockville Pike, Bethesda, MD 20889 5600, USA
[b] Orthopaedic Foot and Ankle Service, National Naval Medical Center (NNMC), 8901 Wisconsin Avenue, Bethesda, MD 20889, USA
[c] Uniformed Services University of the Health Sciences (USUHS), Bethesda, MD, USA
[d] Orthopaedic Surgery Service, Walter Reed National Military Medical Center (WRNMMC), 8901 Wisconsin Avenue, Bethesda, MD 20889, USA
[e] Orthopaedic Surgery Service, Walter Reed National Military Medical Center (WRNMMC), 6900 Georgia Avenue NW, Washington, DC, USA
[f] Brooke Army Medical Center (BAMC), 3851 Roger Brooke Drive, Fort Sam Houston, TX 78234, USA
[g] US Army Institute of Surgical Research, 3400 Rawley East Chambers Avenue, Building 3611, Fort Sam Houston, San Antonio, TX 78234 6315, USA
[h] Orthopaedic Foot and Ankle Service, Walter Reed Army Medical Center (WRAMC), 6900 Georgia Avenue NW, Washington, DC 20307, USA
[i] Orthopaedic Surgery Residency, National Capital Consortium, Bethesda, MD, USA
* Corresponding author. Orthopaedic Foot and Ankle Service, National Naval Medical Center (NNMC), 8901 Wisconsin Avenue, Bethesda, MD 20889.
E mail address: john.keeling@med.navy.mil (J.J. Keeling).

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injuries does not typically present with the characteristic fracture patterns that many orthopedists are trained to manage. This unfamiliarity increases the complexity of preoperative salvage planning and implementation. Because many of the blasts experienced in the current conflicts are ground based, the foot and ankle sustain considerable severity and extent of injury because of their proximity.[1]

Several civilian investigators have previously concluded that the ability to salvage severe open extremity trauma may be more related to the extent of soft tissue compromise than the degree of bone injury.[5–7] The authors' experience in the current conflicts has shown a similar trend, with the magnitude of soft tissue injury usually dictating whether or not salvage may be possible. Furthermore, wartime blast-related foot and ankle trauma frequently requires performance of extensile fasciotomy to prevent the complications of intrinsic muscle death and subsequent joint contractures.[8] This necessity compounds the challenge of managing an already compromised soft tissue envelope. In addition, delays in definitive wound management and provider turnover that are inherent in the evacuation of wounded warriors to the continental United States further challenge the surgeon providing definitive care.

Early, aggressive wound debridement and irrigation is the cornerstone of any effort to salvage a severe open extremity wound. This should be performed meticulously, removing all nonviable soft tissues.[9,10] Dysvascular, nonarticular bone should likewise be removed, regardless of size, and discarded. An intraoperative assessment must then be made by the operative surgeon with plastic and vascular surgery consultation on the likelihood of salvage with an ultimate goal of providing the patient with a painless, noninfected, and functional foot. Numerous scoring systems have been developed to predict the ability to salvage mangled extremities; all have been shown to have weaknesses.[11] Ultimately, a frank intraoperative assessment by at least 2 surgeons who are experienced in limb salvage may be the most consistent way to decide whether a limb has the potential to be saved. Particular attention must be given to those limbs with both a large soft tissue and bone deficit and an associated arterial injury, because these extensively injured limbs have been shown to have a 100% early or delayed rate of amputation.[12]

In most military treatment centers, serial debridement and irrigation at least every 48 hours has become the accepted protocol of wound management. Large bone deficits are filled with antibiotic laden cement spacers to attempt to control local wound bacterial levels and manage dead space. The use of negative pressure wound therapy has become commonplace.[13] Once the wound seems stable, subsequent soft tissue coverage by delayed closure, skin grafting, or vascularized soft tissue flap coverage is performed. Occasionally, vascularized osteocutaneous flaps are performed early, because they have the inherent ability to combat colonizing bacteria.[14] Frequently, a delay of several days to several weeks is allowed to ensure that early deep wound infection has been avoided. A transition from temporary monoplanar external fixation placed in the theater of war to more stable ring external fixator may also be considered if further wound management is not needed.[10]

Once wound closure is successful and infection is avoided, bone defect management may begin. Several strategies are available including vascularized and nonvascularized autogenous bone grafting or allogenic bone grafting. Structural and nonstructural grafts can be used with and without supplemental extenders and bone healing enhancers.[15] In addition, distraction osteogenesis, bone segment shortening/rotationplasty, and fusion all have a role to play in salvaging massive bone defects in the foot. Metal cages with cancellous bone grafting[16] and the use of tantalum[17] have also been described for treatment of bone defects; however, the

risk of deep infection associated with open, contaminated blast trauma has limited their use in the patient population studied by the authors.

FOREFOOT

Injury to individual toes varies in severity. Because of the nature of the blast, most toe injuries frequently result in partial or complete amputation. This is generally tolerated without much functional deficit, and custom toe spacers and shoe fillers are all that is usually needed to prevent subsequent forefoot deformity and accommodate the remaining foot in a shoe.

The great toe may represent the exception. It has been shown to be important during push-off during the later phases of the gait cycle, particularly at quick paces. Strategies to replace great toe bone loss have been previously described. Vascularized bone grafting from the supracondylar ridge of the distal femur represents a viable option for salvage.[18] It may provide the extra benefits of avoidance of infection due to a vascularized block of bone as well as more effective healing and incorporation into the local bone bed.

Fusion of the first metatarsophalangeal (MTP) joint after injury and structural bone loss is also a widely accepted method of treatment.[19] Autograft bone block arthrodesis has been shown to be very effective and well tolerated in active patients.[20] The drawbacks include a secondary surgical site for graft harvest, which can result in the well-known complications of nerve injury, fracture, hematoma, and chronic pain. Myerson and colleagues[19] and other investigators have described the use of structural bone allograft to replace bone loss when attempting fusion in the forefoot. In their series of 24 patients undergoing first MTP allograft bone block fusion, all the patients achieved satisfactory outcome, although 3 required repeat arthrodesis. A 20-year-old male marine sustained a comminuted open left first MTP that was injury initially treated with spanning mini external fixation (**Fig. 1**). Subsequent arthritic collapse and pain necessitated successful allograft bone block arthrodesis.

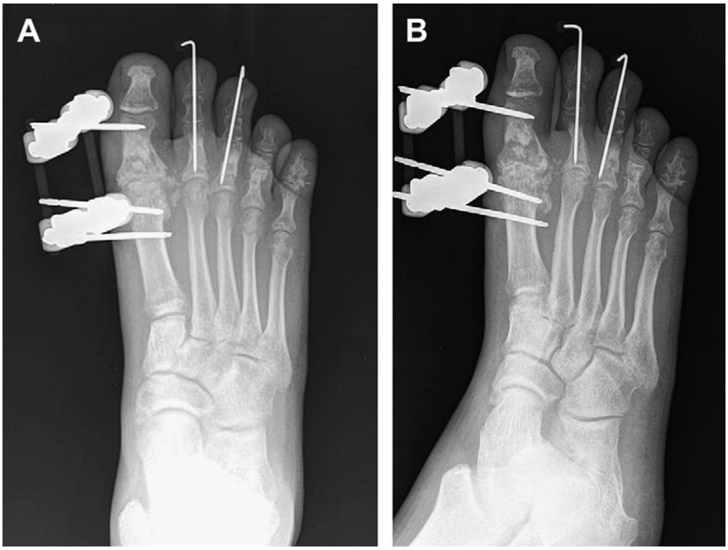

Fig. 1. (*A*) Anteroposterior (AP) radiograph showing extensively comminuted first MTP frac ture stabilized with mini external fixation. (*B*) Oblique foot radiograph showing extensively comminuted first MTP fracture stabilized with mini external fixation.

Metatarsal bone loss has also been addressed in the young active population studied by the authors. A 21-year-old soldier sustained an open fourth and fifth metatarsal bone loss with associated lateral soft tissue deficit with retention of the associated toes (**Fig. 2**). Because the mobile lateral column of the foot can be sacrificed and still maintain an adequate weight bearing lever arm for ambulation, in this case, a partial foot amputation was accepted and the soft tissue from the lateral 2 rays was used for soft tissue coverage of a large soft tissue defect after skeletonizing the toe bones. The patient subsequently recovered most activities, including running, with the use of a lateral shoe filler. The medial column is much more critical for ambulation and should be restored. Strategies include autograft and allograft bone grafting, either structural or cancellous.[21] Defects larger than 1 cm may be best treated with structural grafting. The benefits of a vascularized graft are quicker incorporation and remodeling potential.[22] The downside is graft harvest morbidity, as previously outlined. Structural allograft bone grafts are attractive because of the unlimited supply and reduced donor morbidity. However, some concern persists regarding their potential for complete incorporation and risk of stress fracture during resorption and remodeling.[23] A 25-year-old marine sustained an open right first metatarsal bone loss of 2 cm (**Fig. 3**A). This was successfully managed with allograft bone replacement fixed with internal fixation (**Fig. 3**B).

As a long bone, the metatarsals are also well suited for distraction lengthening. This strategy has been successfully used to address congenitally short metatarsal bones (brachymetatarsalgia) and iatrogenically created short metatarsals, which frequently result in transfer metatarsalgia.[24,25] The benefits of this form of treatment include no donor site morbidity and a strong host bone once the regenerated bone has matured. The downsides include risks of pin tract infection, pain during lengthening, and a lengthy period of non–weight bearing as the lengthening occurs and subsequent non–weight bearing as the regenerated bone matures. The technique is performed by placing a mini external fixator rail with 2 points of fixation at the proximal and distal segments. A corticotomy is then performed and lengthening proceeds at the rate of

Fig. 2. AP foot radiograph showing lateral ray destruction after blast injury.

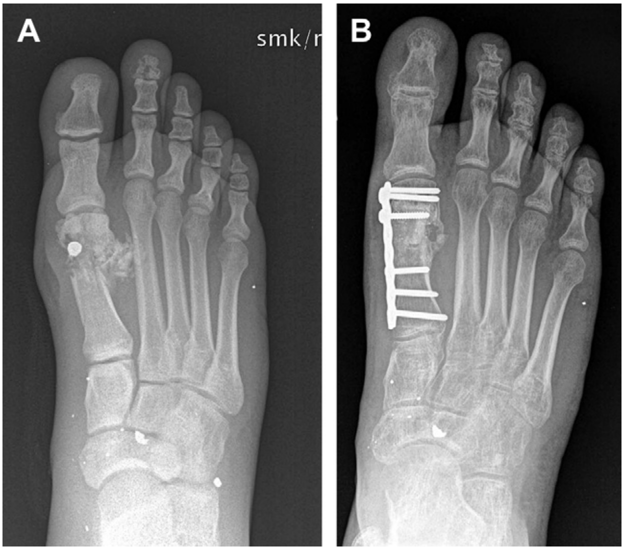

Fig. 3. (*A*) AP foot radiograph showing first metatarsal traumatic segmental defect. (*B*) AP foot radiograph showing first metatarsal segmental defect treated with structural allograft interposition graft.

approximately 1 mm/d. Consolidation time varies, but is usually 2 months for each centimeter lengthened. The authors have not frequently used this method of salvage.

MIDFOOT

Severe comminution and bone loss through the midfoot joints can be difficult to treat. One strategy is to attempt to bridge the area of comminution and bone loss with a stable ring external fixator.[26] This allows for subsequent bony consolidation and fusion by bone callous formation or fibrous scar tissue with a plan to perform selective bone grafting to areas of symptomatic nonunion, if needed, once the patient is healed and has become ambulatory. In addition, the use of a spanning external fixator reduces the burden on the severely injured soft tissues. A 23-year-old marine sustained an open comminuted left Lisfranc fracture dislocation (**Fig. 4**A). He was successfully treated with a spanning ring external fixator, which was removed at 3 months (**Fig. 4**B). Although a subsequent bone grafting procedure was anticipated, he did not require it.

Similarly, a 36-year-old male soldier was treated for a large bone defect in the cuboid (**Fig. 5**A and B), which was successfully managed with spanning monoplanar external fixation, serial irrigation and debridement, and ultimately with calcium sulfate bone void filler. The fracture consolidated and healed without infection, although chronic neuropathic pain persisted in and around the fracture site (**Fig. 5**C), ultimately resulting in amputation.

HINDFOOT

Calcaneal alignment, as one-third of the foot tripod, is critical to maintain appropriate length, width, and height to allow for near normal shoe wear and gait. Bone loss in the calcaneus as a result of high-energy open trauma is often complicated by critical soft tissue loss. Although soft tissue reconstruction techniques for the lateral and posterior

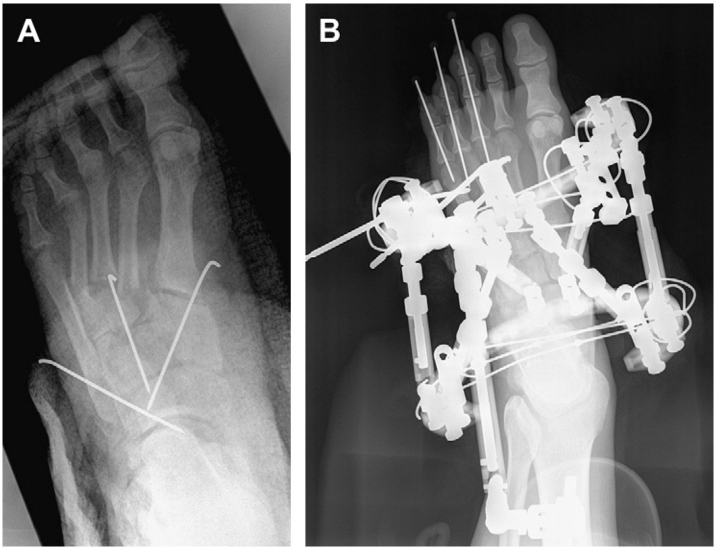

Fig. 4. (*A*) AP foot radiograph showing comminuted midfoot fracture dislocation in blast injured patient. (*B*) AP radiograph of the foot treated with spanning ring external fixation.

aspects of the calcaneus have been used with fair success,[14,27,28] there are limited options for reliable reconstruction of the plantar fat pad.[29] Plantar soft tissue wounds are known to predict poor outcomes for open calcaneus fracture.[5] A 21-year-old marine sustained an open type-IIIB calcaneus fracture with severe plantar soft tissue disruption necessitating amputation (**Fig. 6**). It is unclear whether attempted soft tissue transfers can reproduce the function of the plantar fat pad, and the authors have not routinely used such transfers.

Fig. 5. (*A*) Oblique foot radiograph with associated cuboid bone loss from blast. (*B*) CT scan demonstrating near complete cuboid bone loss. (*C*) Oblique foot radiograph demonstrating healed cuboid bone defect.

Fig. 6. Disrupted heel pad in blast injured extremity.

Extra-articular bone loss in the calcaneus can be managed in various ways depending on the extent, presence or absence of infection, and the soft tissue envelope. There are several series that document the use of bone graft substitutes in conjunction with internal fixation of calcaneus fractures.[15,21,30] Other techniques for managing bony defects in the calcaneus involve utilization of autogenous or allograft bone.[6,14,23] Some investigators have used these techniques in combination with a local antibiotic.[31] This recent series demonstrated a low infection rate by combining vancomycin with an allograft bone mixture. A 25-year-old marine was treated with combined internal and external fixation, massive allograft, and rhBMP-2 (recombinant human bone morphogenetic protein) (INFUSE; Medtronic Sofamor Danek, Memphis, TN, USA) combined with vancomycin powder for a large bone void in the calcaneus (**Fig. 7**A). A similar method of treatment was also applied to an ipsilateral open talar neck fracture with 1-cm bone loss (**Fig. 7**B). The patient's fractures healed without

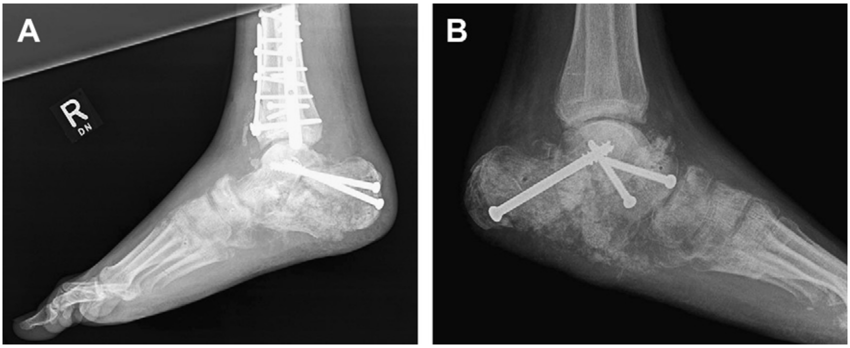

Fig. 7. (*A*) Lateral foot radiograph showing open calcaneus fracture with bone loss treated with massive allograft, rhBMP, and vancomycin powder. (*B*) Lateral foot radiograph showing open talar neck fracture with 1 cm bone loss treated with allograft, rhBMP, and vancomycin powder.

infection, although he continued to have a chronically painful right foot and ankle, which ultimately required amputation.

In the case of an infected bony defect with a concomitant soft tissue loss, the Papineau technique can still be considered.[32] A "modern" version of this technique involves utilization of subatmospheric wound therapy (VAC; Kinetic Concepts, Inc, San Antonio, TX, USA).[33]

Intra-articular bone loss from the calcaneus resulting from blast injury frequently requires subtalar fusion. Augmenting the fusion with autograft or allograft may be necessary depending on the amount of bone loss and need to reconstruct anatomic calcaneal height.[15,21,23] Although large amounts of bone graft may require harvest from the iliac crest, a safe and reliable source of autograft bone for foot and ankle surgery is the patient's ipsilateral proximal tibia.[34] Alternatively, the remaining calcaneal bone stock can be realigned for in situ fusion or rotationplasty avoiding the need for large amounts of bone graft (**Fig. 8**).

The talus plays a critical role in gait and stance. The talus serves a unique role in the body as the junction between the vertical elements of the skeleton and the horizontal terminal weight bearing extremity. The complexities of its many articulations are evidence of this pivotal role in bipedal gait and stance. Fractures of the talus that involve some bone loss in the region of the neck can be managed with fixation methods such as plating that maintains length and alignment.[35] Misalignment of talar neck fractures significantly changes the mechanics and contact stresses of the subtalar joint and can contribute to poorer outcomes.[36]

Successful management of talar bone loss due to extrusion, infection, or avascular necrosis is extremely difficult. Tibiocalcaneal fusion typically leaves a patient with a leg length discrepancy unless large bone grafts are used.[37] Bifocal reconstruction techniques with distraction osteogenesis at a different site can be used to perform the fusion and restore the limb length simultaneously.[38] A 31-year-old marine was treated for an extruded talus with ring external fixation and tibial lengthening in an effort to perform tibiocalcaneal fusion (**Fig. 9**). Reconstructive techniques such as the Blair fusion have had mixed results in the literature and have not been frequently attempted in the patient population studied by the authors.[39,40] Although BMP use has been well studied in the tibia and has been used in foot and ankle reconstructions, its role is poorly defined.[41]

SUMMARY

Bone loss caused by blast-related trauma or secondary infection in the foot and ankle continues to be a difficult problem. The high functional demands required of active

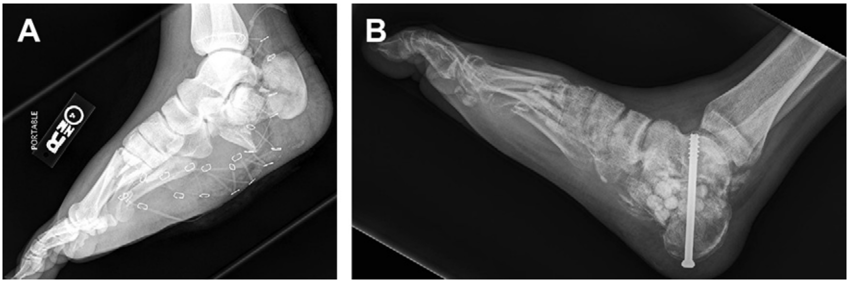

Fig. 8. (*A*) Lateral foot radiograph demonstrating large segmental loss of the calcaneus. (*B*) Lateral foot radiograph illustrating calcaneal "rotationplasty" to treat bone loss with an immediate subtalar fusion.

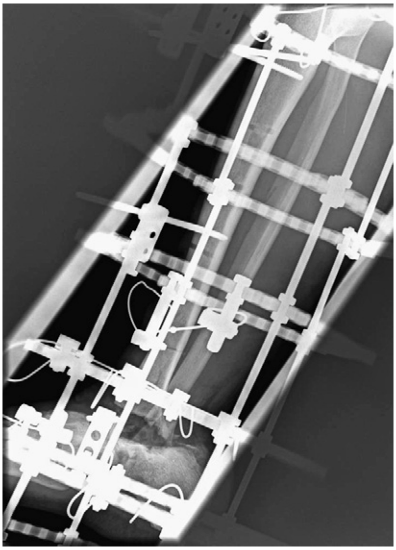

Fig. 9. Lateral tibia/fibula radiograph illustrating the use of ring external fixation with tibial lengthening to attempt tibiocalcaneal fusion due to talar loss after extrusion.

service members, also create several reconstructive challenges. Because many of these injured warriors have expectation to return to duty, the demands of service require advanced techniques to obtain adequate outcomes. Even simple uniform requirements affect the service member's perception of his/her reconstruction. Furthermore, occupational requirements such as marching and running on uneven ground require adequate functional motion and a sufficient calcaneal fat pad to tolerate the effect.

It is not a stretch to state that the "terminal extremity" drives the success of limb salvage surgery in many of these patients. Moreover, continued research and application of new and improved techniques to address these severe injuries are needed to provide a functional and painless distal extremity in comparison to the high-demand amputee with a well-fitting prosthesis.

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